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Published in:
Antennas and Propagation (EuCAP), 2014 8th European Conference on

DOI (link to publication from Publisher):
10.1109/EuCAP.2014.6902199

Publication date:
2014

Document Version
Early version, also known as pre-print

Citation for published version (APA):
Buskgaard, E. F., Tatomirescu, A., Barrio, S. C. D., Franek, O., & Pedersen, G. F. (2014). User Effect on the MIMO Performance of a Dual Antenna LTE Handset. In Antennas and Propagation (EuCAP), 2014 8th European Conference on (pp. 2006-2009). IEEE. DOI: 10.1109/EuCAP.2014.6902199

User Effect on the MIMO Performance of a Dual Antenna LTE Handset

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***Abstract*—This study focuses on the user influence on a MIMO antenna system in a smart phone form factor. The antenna system is designed to have a low coupling and correlation between its two antennas. The study is based on time-domain simulations of the antenna system in free space and with a head and hand phantom using a commercially available Finite Element Method solver. The MIMO parameters are evaluated with three different channel models.**

A static grip only gives one case of the user effect so the hand phantom is modified with a moving finger that is swept across the backplane of the phone. Based on the results of the study it is concluded that the placement of the index finger has a significant effect on the simulated antenna system. For certain finger placements the mismatch loss and absorption loss both change more than 5 dB.

Overall the antenna system shows good MIMO performance in free space but suffers under the influence of the user. Especially the diversity antenna is heavily detuned and gives a total efficiency of -19.1 dB worst case compared to -1.9 dB in free space. The branch power ratio is increased by the user while the envelope correlation is decreased by the user.

***Index Terms*—MIMO,**

I. INTRODUCTION

WITH the introduction of Long Term Evolution (LTE) Multiple Input Multiple Output (MIMO) has become a common requirement for mobile phones. The benefit in terms of throughput of MIMO can be huge for a well designed antenna system where the antennas are sufficiently decorrelated and isolated. If the correlation is too strong between the antennas the data streams are harder to separate and the throughput is reduced. For Signal to Noise Ratio (SNR) limited MIMO links the throughput is limited by the Branch Power Ratio (BPR) as well. In this case if one antenna is receiving significantly more power than the other then the weaker antenna link will have a lower SNR and thus not be able to support as high a data rate as the strong link.

The effect of the user has long been acknowledged as a major influence on mobile antenna performance [1]–[4]. It both absorbs power as well as detunes the center frequency of the antenna. Absorption loss is intrinsic to the interaction with a user. The absorption loss varies depending on the antenna type and user hand and head size and grip style. The absorption in the hand and head of the user will be beneficial for isolation between the MIMO antennas but the user may also compromise the orthogonality of the ground currents caused by the two antennas according to the characteristic mode theory [5], [6] causing the isolation to decrease.

This study looks at the correlation and coupling between two antennas in a Down-Link (DL) MIMO setup for LTE Band 13. The main antenna is covering both the Rx and the Tx frequencies while the diversity antenna only covers the Rx portion of Band 13. The designed MIMO antenna configuration is evaluated based on Computer Simulation Technology (CST) [7] simulations. For each configuration the free space performance is compared to the performance under influence of the CTIA Specific Anthropomorphic Mannequin (SAM) head phantom and the CTIA hand model for talk position [8]. Section II will specify the antenna design that has been developed for this study as well as the modeling of the user. In Section III the simulation procedure and the different channel models used for the MIMO parameters are described. Section IV presents and discusses the results while the conclusion of the study is formulated in Section V.

II. SIMULATION SETUP

All simulations are performed on a MIMO antenna system for LTE Band 13 in the presence of the CTIA SAM head and the CTIA hand. Band 13 is a very challenging LTE band since the frequency is low and the phone PCB therefore becomes electrically short. Fig. 1 shows the antenna system consisting of a ground plane (GND) with two folded monopole antennas. The antenna at the end of the GND is the main antenna covering all of Band 13 (746 - 787 MHz) while the side antenna is the diversity antenna only covering the RX band (746 - 756 MHz). Each antenna is matched with an inductor in parallel to the port. The antenna system is enclosed in a housing with sides made of 1 mm thick plastic and front and back made of 0.5 mm plastic. All dimensions of the antennas and housing are listed in Table I. This table also includes a list of materials and their parameters as well as the values of the parallel matching inductances.

To quantify the effect of the antenna placement on the immunity to the user the antenna system is simulated both with the main antenna at the top of the phone (close by the ear) and the diversity antenna on the side, Top-Side (TS), and at the bottom and side, Bottom-Side (BS). The antenna system is not changed between TS and BS but only rotated 180° inside the casing. This means that both the main and diversity antenna

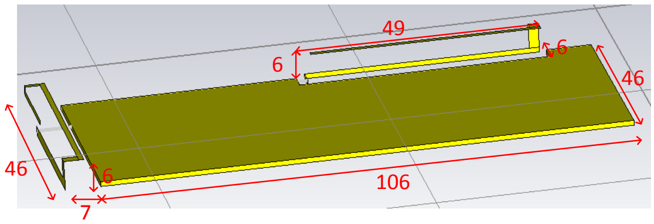

Fig. 1. Dimensions of the simulated PCB with MIMO antenna setup.

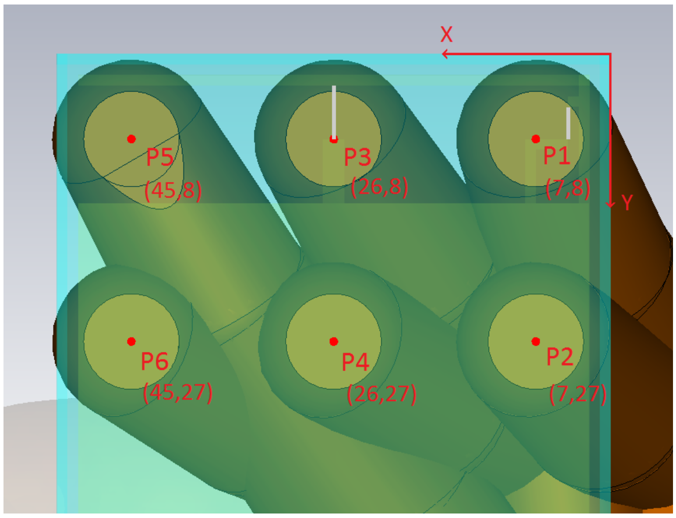

Fig. 2. Index finger positions used for simulations of hand effect. Coordinates are in mm from the top right corner of the phone. Finger tip is touching the backside of the phone in the light brown regions.

is changing position with respect to the user but the phone performance does not change in free space (FS)

The phone models are placed into a modified CTIA hand where the index finger has been replaced by a parameterized model that can be moved over the back plane of the phone. The dimensions of the parameterized finger are taken from [8]. The material is identical and all dimensions are kept in line with the CTIA specification. The angles of the bends in the finger are changed within the realistic movement of the finger. The finger tip is swept across the six positions shown on Fig. 2.

To get a realistic simulation of the losses in talk mode the influence of the head must also be included. This is done by adding a model of the CTIA specified SAM. It consists of an outer shell filled by a liquid that emulates the properties of the human head. The properties at the chosen frequency band are listed in Table I.

III. SIMULATION PROCEDURE

The simulations presented are done using the transient solver of CST. It utilizes the Finite Element Method (FEM) to simulate the response of the 3D structure to a short pulse that is exciting all frequencies of interest. A hexahedral mesh is chosen with minimum 20 mesh cells per wavelength.

First a baseline simulation is done for the antenna, ground plane and housing without the SAM phantom and CTIA hand. The dimensions of the antennas are adjusted to tune the antennas and values of the parallel inductors are adjusted to match the antennas. Then the head and hand are added and the position of the tip of the index finger is swept across the six positions shown on Fig. 2. For each position a simulation is done and the results are compared to the free space baseline. This is done to investigate the existence of sensitive spots on the ground plane, and their effect on antenna performance. Performance limitations due to the user interaction are more likely found by this procedure.

TABLE I
ANTENNA CONFIGURATION DIMENSIONS AND MATERIAL PROPERTIES

Antenna Dimensions [mm]:			
Name	**H**	**W**	**T**
Primary	7	46	6
Diversity	6	49	6
PCB	106	46	1
Housing	117	52	8
Material properties @ 751 MHz:			
Part	**Material**	ε_r	**tan** δ
Casing	Plastic	2.8	0.002
Hand	CTIA spec	31.8	0.421
Head shell	CTIA spec	3.5	0
Head fill	IEEE1528 liquid	41.8	0.504
Antennas	Copper	σ = 5.96e7 S/m	
Matching inductance parallel to feed:			
$\mathbf{L}_{Feed}$	Primary: 5.5 nH	Diversity: 3.0 nH	

The results of the simulations are sets of S-parameters from the two antennas and antenna patterns for each antenna. From the antenna patterns, the envelope correlation and branch power ratio (BPR) between the antennas is calculated. The cross correlation is calculated for three different channel models:

Isotropic The isotropic channel model is the simplest and least realistic. It assumes a completely uniform power distribution from all directions. This gives the most optimistic result for correlation between the antenna patterns of the two antennas.

Gaussian The Gaussian channel model was introduced in [9] by Taga. Building on analysis of antennas moving around in a mobile communication environment, this model gives a statistical representation of the incident power distribution for an antenna. The model assumes equal probability of the power from all directions in the horizontal plane and a Gaussian distribution across elevation with maximum in the horizontal plane. It is a multi-path environment with cross polarization (XPD) of 1, and for vertical, V, and horizontal, H, polarizations the mean elevation, m, and standard deviation, σ, are:

$$
\begin{aligned}
\text{XPD} &= 3\ \text{dB} \\
m_V = 0^\circ &\quad \sigma_V = 40^\circ \\
m_H = 0^\circ &\quad \sigma_H = 60^\circ
\end{aligned}
$$

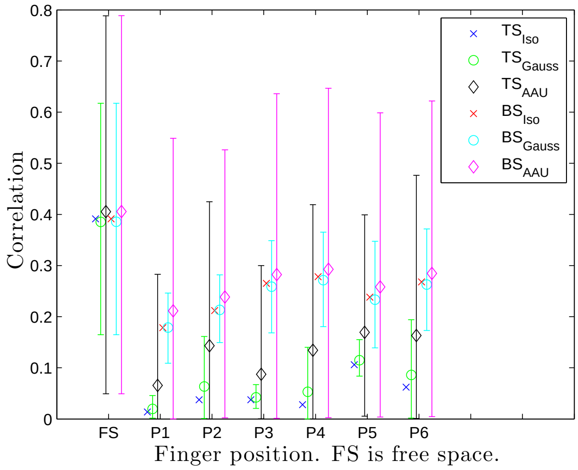

Fig. 3. Simulated correlation between main and diversity antenna at 751 MHz for Isotropic, Gaussian and AAU environment. TS is top-side antenna configuration while BS is bottom-side configuration.

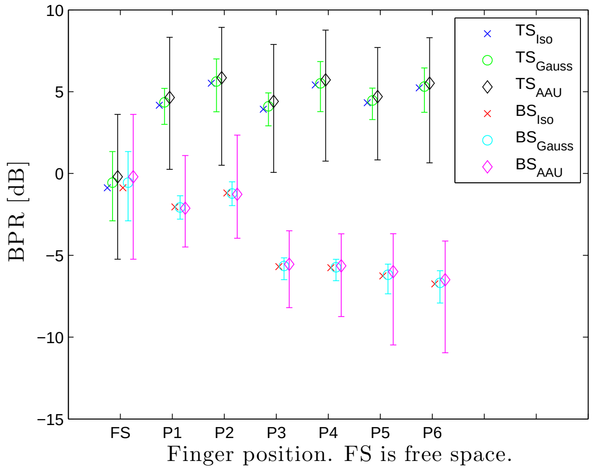

Fig. 4. Simulated BPR between main and diversity antenna at 751 MHz for Isotropic, Gaussian and AAU environment. TS is top-side antenna configuration while BS is bottom-side configuration.

AAU The AAU channel model was introduced in [10] as a realistic channel model for outdoor to indoor environments. The model is based on live measurements that showed that radio signals primarily enter a building through the windows. Therefore the model assumes that the majority of the power comes from one direction. [10] lists the parameters for the model based on experimental data. These values are used for the model in this paper as well.

IV. RESULTS

This paper focuses on the added information that the array of finger positions gives. To evaluate the added value of the finger position sweeping simulated values for both single antenna parameters as well as array parameters are presented. The parameters are presented for free space (FS) and for each of the six finger positions (P1 to P6) shown in Fig. 2. Results are presented for both the TS and BS antenna configuration described earlier.

Fig. 3 shows the correlation between the antennas. Data series are included for the three different channel models for both the TS and BS configuration. The antenna systems are rotated in 30° intervals on azimuth, elevation and orientation with respect to the incoming power distribution of the channel. For the Isotropic channel model the power distribution is completely uniform from all directions so spinning the phone yields the same result for all angles. Therefore the data series of the Isotropic model has only one value per finger position. For the Gaussian and AAU models there is a spread of the correlation across all orientations of the phone. Here, the minimum, mean and maximum values are all included on the graphs.

The antenna system is designed to have low correlation between the two antenna patterns and it achieves approximately 0.4 in FS as an average value. This is a good performance. The head and hand improves the correlation for all finger positions. The finger movement does not make a clear difference in the correlation values.

The finger position has a more clear effect on the BPR as seen in Fig. 4. The data series on this figure are generated and organized in the same way as on Fig. 3. Here the head and hand deteriorates the BPR by up to 10 dB. For TS the BPR is only mildly affected by the movement of the finger. There is a vague trend that the lower finger positions give worse BPR but it is not pronounced. For BS though the effect of the finger is noticeably different for P1 and P2 than for the rest. Here the proximity of the finger to the side antenna is helping to keep the branch power balanced giving a clear difference in performance on this parameter.

Table II shows the S-parameters of the two antenna configurations. Here especially the reflection coefficient of the top mounted antenna (S_{11} of TS) is showing a strong influence of the finger position. For the upper finger positions the top antenna is detuned more than for the lower. This is to be expected since the upper finger positions are on top of the antenna where as the lower positions are just below it. There is a trend in S_{22} for BS showing 1 dB higher reflection coefficient for P1 and P2. This extra detuning results in several dB's of additional reflection. This also affects S_{21} that improves due to the added mismatch loss of the side antenna. In the TS configuration the side antenna is heavily mismatched by the user as well but equally for all finger positions.

Certain S-parameters show clear dependencies on the finger position. This indicates that the finger position is important for the S-parameters as well. A model like the proposed with a movable index finger provides additional information about the user induced performance degradation compared to the standard CTIA hand.

In Table III the radiation and total efficiencies are listed for each of the antennas in each of the antenna systems. R1 and R2 are the radiation efficiencies and T1 and T2 are the total efficiencies for the main and diversity antennas respectively. The effect of the head and hand is large on these parameters.

TABLE II
S-PARAMETERS OF TOP AND BOTTOM MOUNTED MIMO ANTENNA SYSTEM WITH CTIA HAND AND HEAD AT 751 MHZ. DATA FOR 6 DIFFERENT POSITIONS OF THE INDEX FINGER ARE COMPARED TO THE DATA IN FREE SPACE. ANTENNA 1 IS TOP OR BOTTOM MOUNTED AND ANTENNA 2 IS SIDE MOUNTED.

	Antennas: Top/side			**Antennas: Bottom/side**		
	S_{11}	**S_{22}**	**S_{21}**	**S_{11}**	**S_{22}**	**S_{21}**
FS	-7.9	-8.2	-8.4	-7.9	-8.2	-8.4
P1	-2.4	-1.2	-22.7	-5.5	-1.1	-21.0
P2	-4.8	-1.2	-22.5	-5.5	-0.6	-22.9
P3	-2.0	-1.2	-22.8	-5.1	-1.8	-19.7
P4	-4.8	-1.2	-22.2	-5.2	-1.9	-19.2
P5	-1.5	-1.1	-22.6	-4.8	-2.6	-19.4
P6	-4.3	-1.1	-22.5	-5.0	-2.0	-18.5

TABLE III
RADIATION AND TOTAL EFFICIENCY OF TOP AND BOTTOM MOUNTED MIMO ANTENNA SYSTEM WITH CTIA HAND AND HEAD AT 751 MHZ. DATA FOR 6 DIFFERENT POSITIONS OF THE INDEX FINGER ARE COMPARED TO THE DATA IN FREE SPACE. ANTENNA 1 IS TOP OR BOTTOM MOUNTED AND ANTENNA 2 IS SIDE MOUNTED.

	Antennas: Top/side				**Antennas: Bottom/side**			
	R1	**R2**	**T1**	**T2**	**R1**	**R2**	**T1**	**T2**
FS	-0.2	-1.1	-1.0	-1.9	-0.2	-1.1	-1.0	-1.9
P1	-13.4	-9.2	-15.8	-14.8	-8.9	-10.9	-9.6	-17.0
P2	-14.1	-8.6	-14.7	-14.6	-8.6	-9.7	-9.0	-18.5
P3	-13.3	-9.3	-16.2	-14.9	-8.7	-14.4	-9.7	-18.5
P4	-14.3	-8.9	-14.9	-14.9	-8.6	-14.4	-9.6	-18.2
P5	-14.0	-9.6	-17.6	-15.5	-8.9	-15.2	-9.9	-18.8
P6	-14.0	-8.8	-14.6	-15.0	-8.7	-15.4	-9.7	-19.1

Again, the effect of the index finger is most visible for the side antenna in the BS configuration. Here R2 is 4 to 5 dB better for P1 and P2 than for the other finger positions. The difference is evened out in T2 because of the larger mismatch loss for P1 and P2. For TS, T1 is having a bit of variation between upper and lower finger positions which is also due to the difference in mismatch loss.

V. CONCLUSION

This paper has investigated the MIMO performance of a dual antenna system. The system is built from two antennas that are decoupled by placing them such that they excite different modes on the ground plane. The antenna system is encased in a plastic casing and tuned to LTE band 13 by adjusting the length of the antenna trace. The aim of the study is to quantify the spread of correlation and coupling between the antennas in the presence of the user. The phone is placed in talk position with a CTIA head and hand. The phone is simulated both with the main antenna pointing up and down.

This setup is simulated using CST. The user effect is simulated by using imported simulation models of the CTIA head and hand phantoms. The CTIA hand is refined with a parametric flexible model of the index finger. Six positions on the back plane of the phone are simulated.

The data shows that the MIMO performance is good in free space. The average values for both correlation and BPR are not affected by the channel model but the variation increases with the directivity of the channel model. For worst case orientations of the phone in the highly directional AAU channel model, the correlation becomes a bit too high, almost 0.8. In all other situations the correlation is between 0.0 and 0.6 which is estimated to be good enough for MIMO. When adding the head and hand of the user the coupling is reduced by more than 10 dB. The average BPR is around 0 dB in FS and increasing with head and hand to 5 dB for TS with worst case values in the AAU channel model reaching almost 10 dB. For BS the average BPR is close to 0 dB for P1 and P2 but more than 5 dB for all other finger positions. The worst case BPR for BS exceeds 10 dB. The primary antenna total efficiency is down to -17.6 dB with the head and hand from -1.0 dB in FS. The diversity antenna has a worst case total efficiency of -19.1 dB compared to -1.9 dB in FS.

The diversity antenna is detuned significantly in both the TS and BS configuration. S_{22} increases from -8.2 dB in FS to -1.1 dB worst case for TS and from -8.2 dB in FS to -0.6 worst case for BS with head and hand. The main antenna is less affected by the user but it does suffer up to 6.4 dB increase in S_{11} for TS when the finger is placed on top of the antenna.

It is clear that the finger position is affecting certain parameters of the antennas significantly. The BPR, radiation efficiency and mismatch are all dependent on finger position. Since the grip style of cell phone users does vary a lot it is an important addition to the CTIA model to include this variation. For instance the mismatch loss of the side antenna in the BS configuration varies by roughly 5 dB for across index finger positions. If adaptive matching should be designed for this antenna system then this could be important information for the requirements for the antenna tuner.

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